Georgia Tech

ECE 4813

Semiconductor Device and Material Characterization

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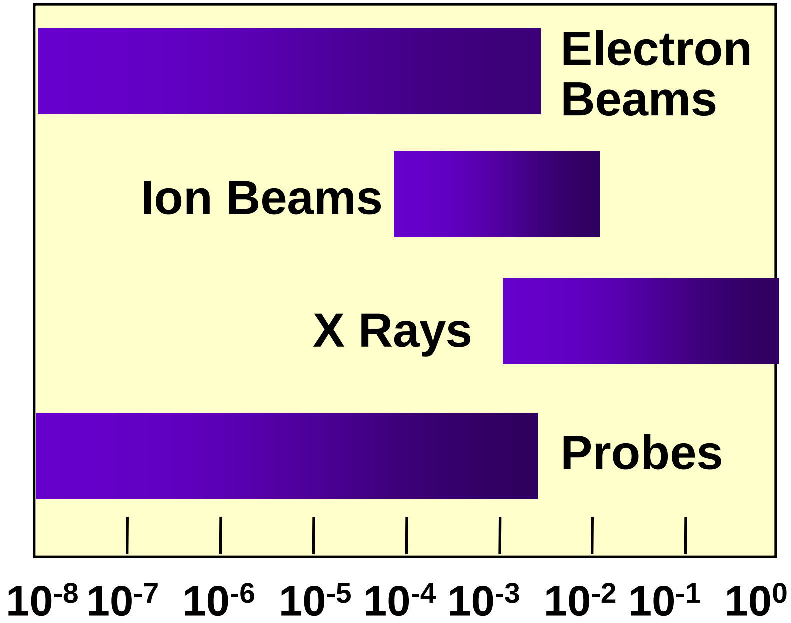
As with all of these lecture slides, I am indebted to Dr. Dieter Schroder from Arizona State University for his generous contributions and freely given resources. Most of (>80%) the figures/slides in this lecture came from Dieter. Some of these figures are copyrighted and can be found within the class text, *Semiconductor Device and Materials Characterization*. ***Every serious microelectronics student should have a copy of this book!***

Electron Beam Characterization

Scanning Electron Microscopy
Transmission Electron Microscopy
Auger Electron Spectroscopy
Electron Microprobe

Sampled Area

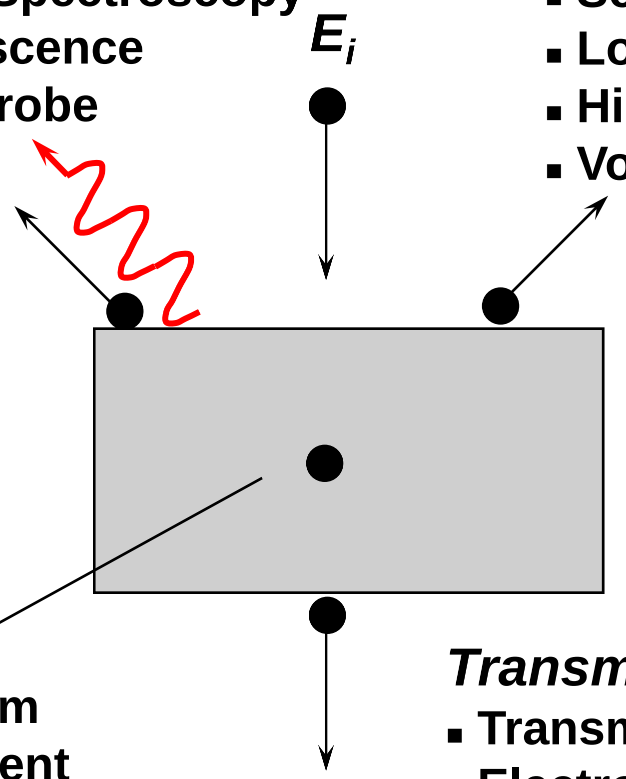


Analytical Diameter (cm)

Electron Beam Characterization

Emission
- Auger Electron Spectroscopy
- Cathodoluminescence
- Electron Microprobe

Reflection
- Scanning Electron Microscopy
- Low Energy Electron Diffraction
- High Energy Electron Diffraction
- Voltage Contrast

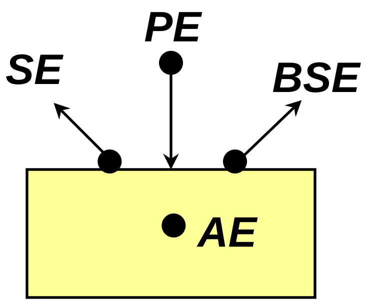


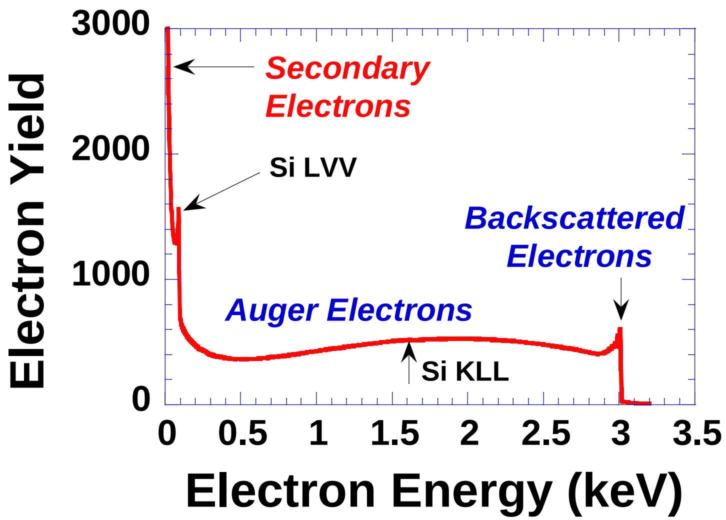
Absorption
- Electron Beam Induced Current

Transmission
- Transmission Electron Microscopy
- Electron Energy Loss Spectroscopy

Electron Yield

- Primary electrons (*PE*) incident on a solid give:
  - Absorbed electrons (*AE*)
  - Secondary electrons (*SE*)
  - Backscattered electrons (*BSE*)
- Secondary electron yield maximum at $E \approx$ 1-3 eV
- *SE*s used in scanning electron microscopy (SEM) and voltage contrast





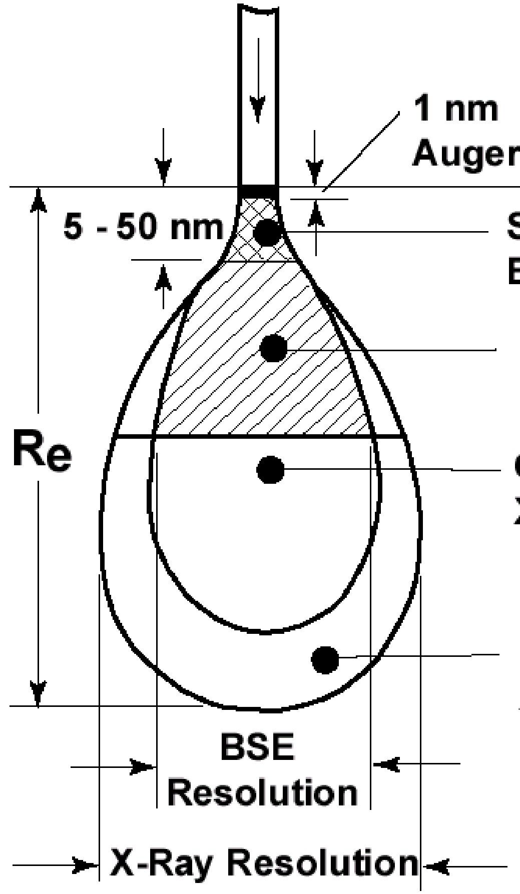
Electrons in a Solid

- Electrons accelerated to 1 - 30 keV
- Beam can be focused to a few Angstrom diameter
- In the solid the beam "blooms" out to electron range R_e

$$R_e = \frac{4.28x10^{-6} E^{1.75}(keV)}{\rho(density)} cm$$

$$R_e = 1.84x10^{-6} E^{1.75}(for\ Si)\ cm$$

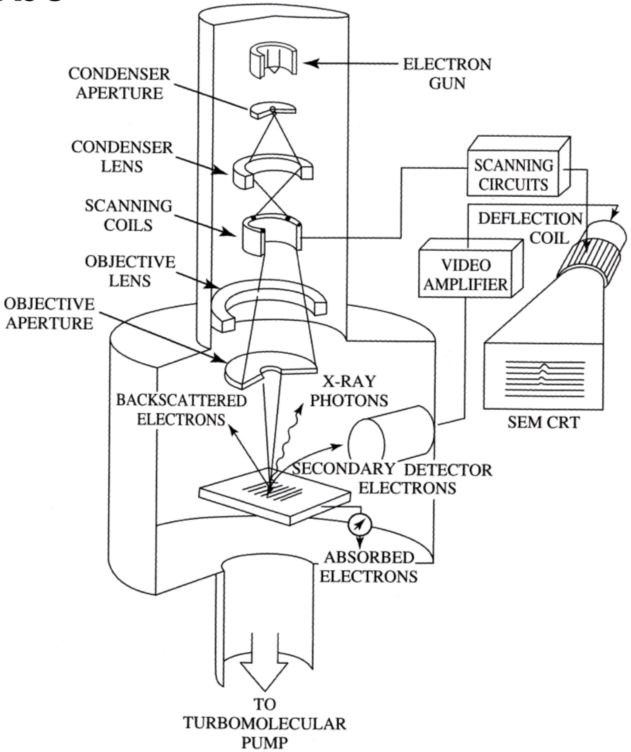
$R_e \approx 1\ \mu$m for E = 10 keV in Si

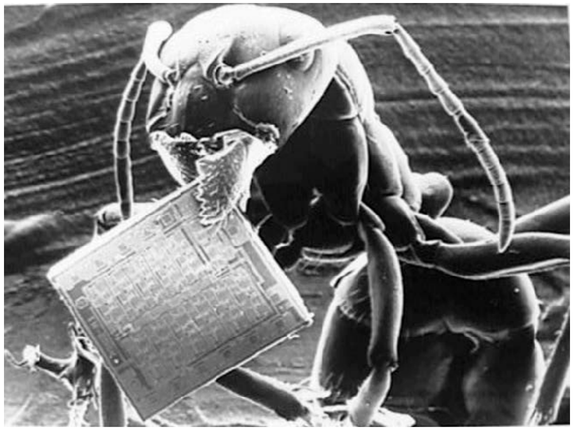


- Since secondary's come from liberated core electrons, their energies are low and thus, only near surface electrons escape.

Scanning Electron Microscopy (SEM)

- Routinely used for semiconductors
  - Line width
  - Topology
- Cathodoluminescence
  - Light emission
- Electron microprobe
  - X-ray emission





SEM Wavelength, Magnification

- The wavelength of an electron is

$$\lambda = \frac{h}{mv} = \frac{1.2}{\sqrt{V}}\ (nm);\ V = 10^4\ V \Rightarrow \lambda = 0.012\ nm$$

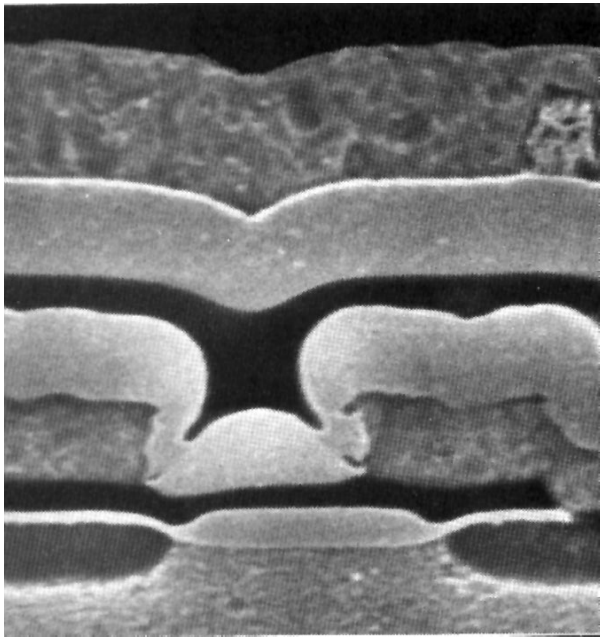
- SEM magnification is given by

$$M = \frac{Length\ of\ CRT\ Display}{Length\ of\ Sample\ Scan} \approx \frac{10\ cm}{1\ \mu m} = 10^5$$

High magnification easy to achieve in an SEM

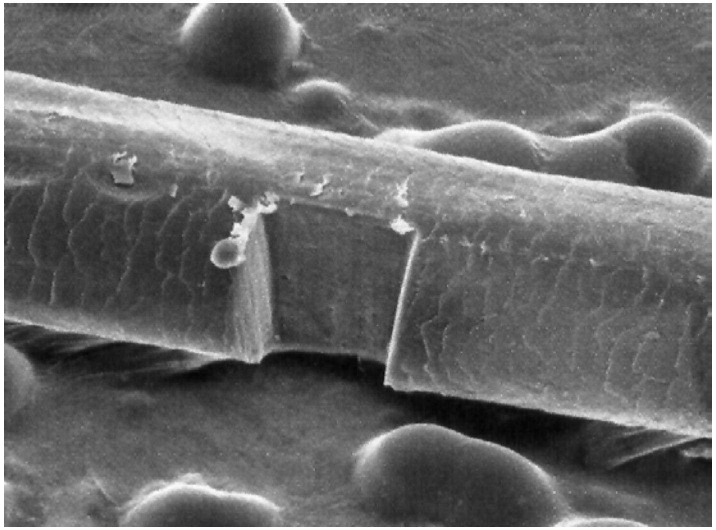
Scanning Electron Microscopy (SEM)

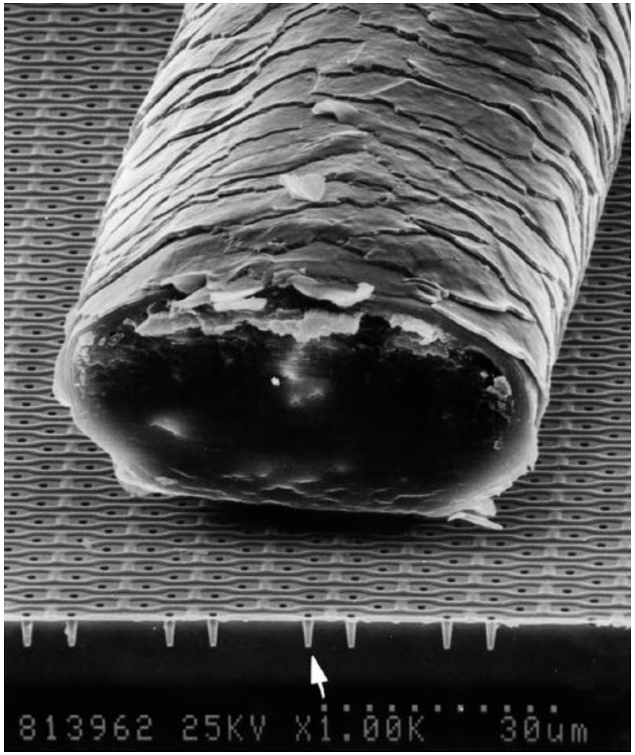
- Contrast depends on angle of incidence of electrons



Scanning Electron Microscopy

- Secondary electron yield depends on
  - Topography
  - Electric Field

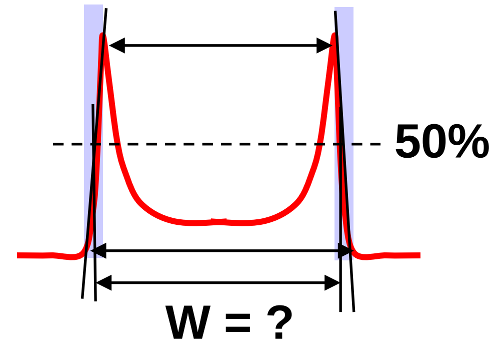


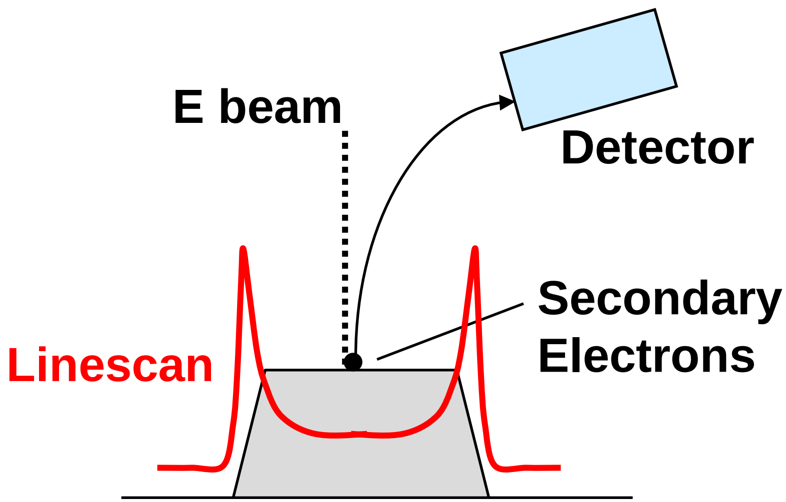


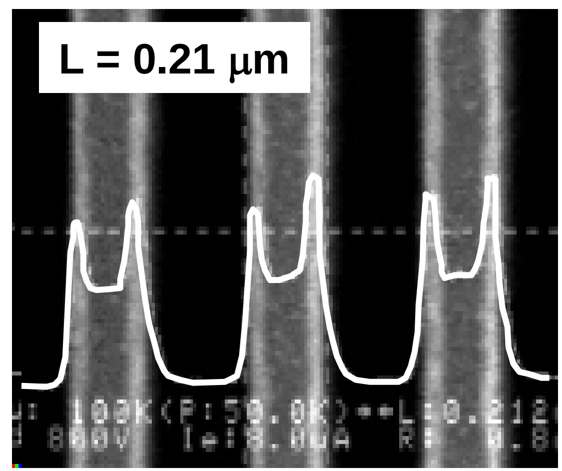
Courtesy Siemens Corp.

Line Width

- Low energy (≲ 1 keV) beam
- Secondary electron emission is topography dependent, e.g., slope surfaces
- Drift, charging
- Magnification
- Line slimming: *e*-beam radiation can cause the photoresist to cross-link and shrink







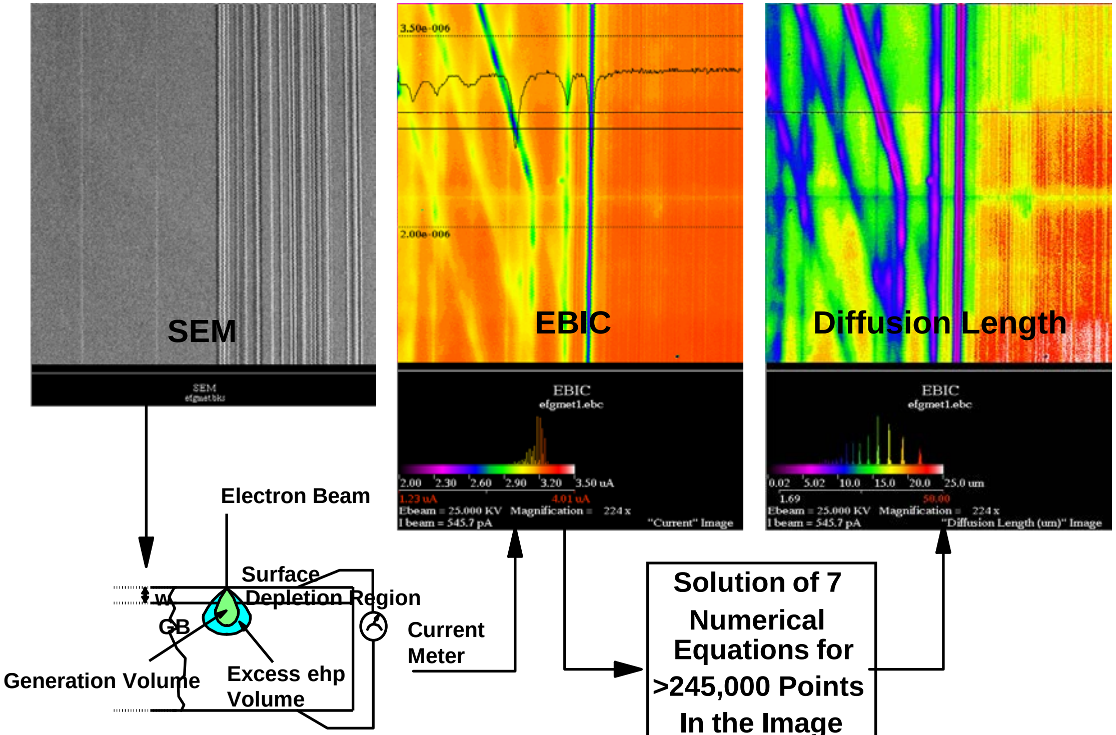
Micrograph courtesy of M. Postek, NIST

Electron Beam Induced Current

- Uses High energy electron beam analogously to light in a solar cell or photodiode to create electron-hole pairs
- The ehps must then be collected as current by a rectifying junction (Schottky or p-n junction, etc…)
- Provides an electrical response map of the material/device.

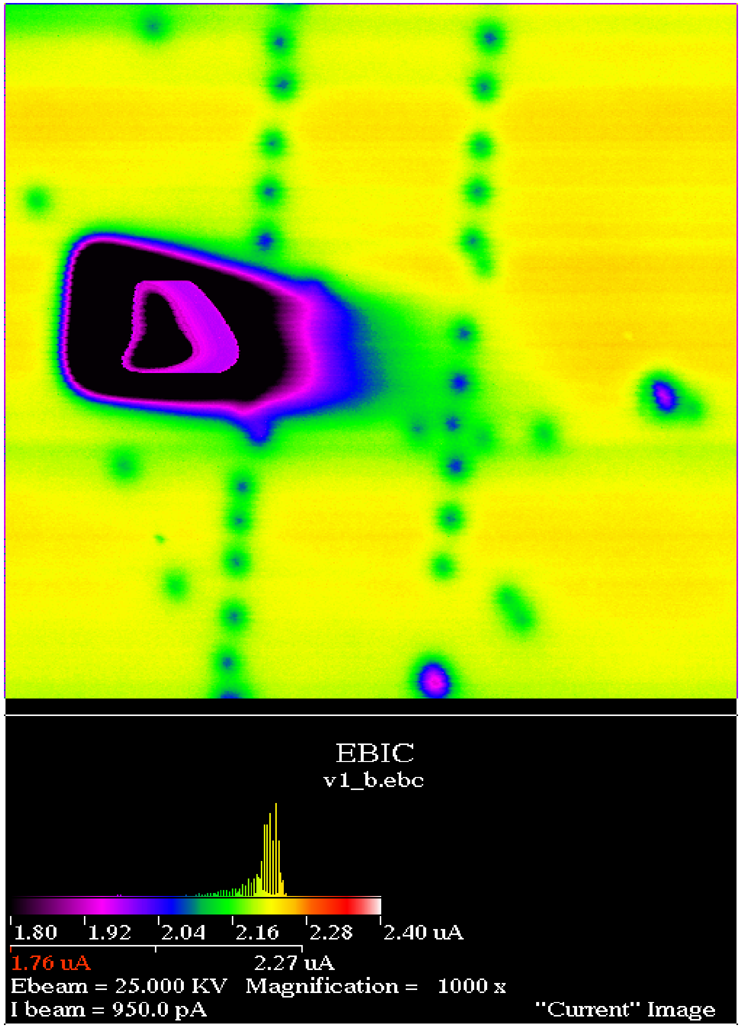
- Scanning Electron Microscope (SEM) Image of an edge Film Silicon sample
- Electron Beam Induced Current Diffusion Length Map (EBIC-DLM) Image of the edge Film Silicon sample to the left obtained by quantitative analysis of the EBIC image.
- Electron Beam Induced Current (EBIC) Image(center) of the edge Film Silicon sample to the left. Note detection of electrically active defects (diagonal lines) not seen in SEM image.

Electron Beam Induced Current (EBIC) and EBIC Diffusion Length Mapping System (EBIC-DLM)

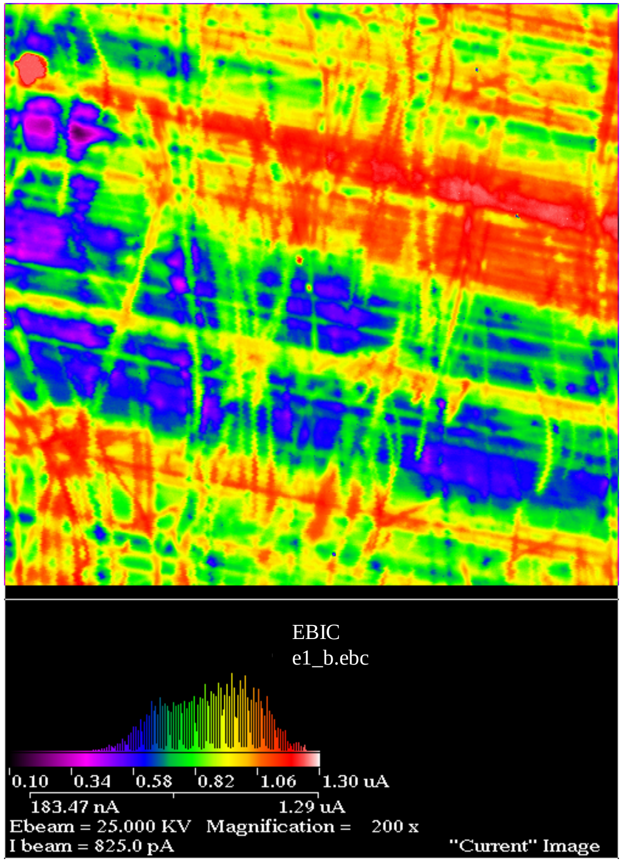


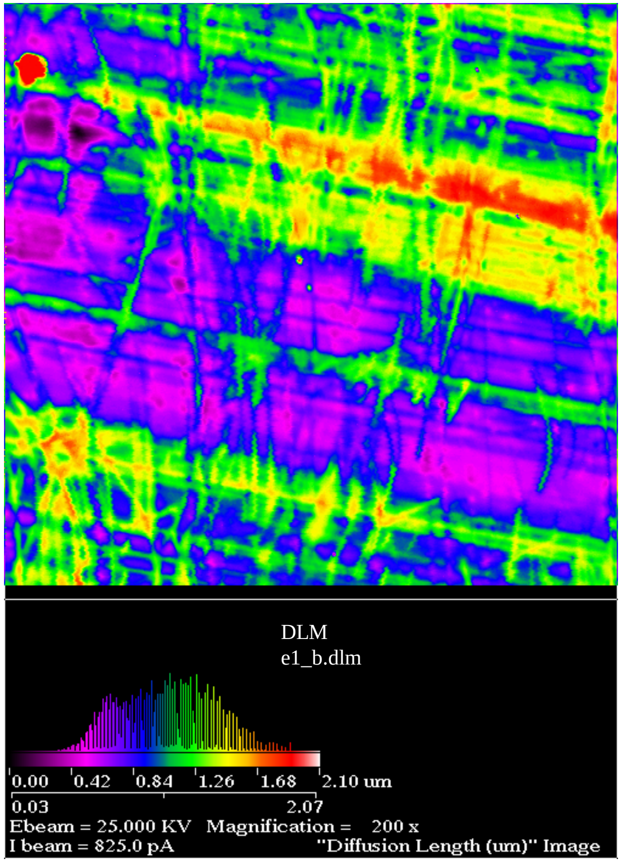
Electron Beam Induced Current

EBIC image showing electrically active defects such as growth step edge decoration and large 3C inclusion in a SiC epitaxial sample.



Electron Beam Induced Current

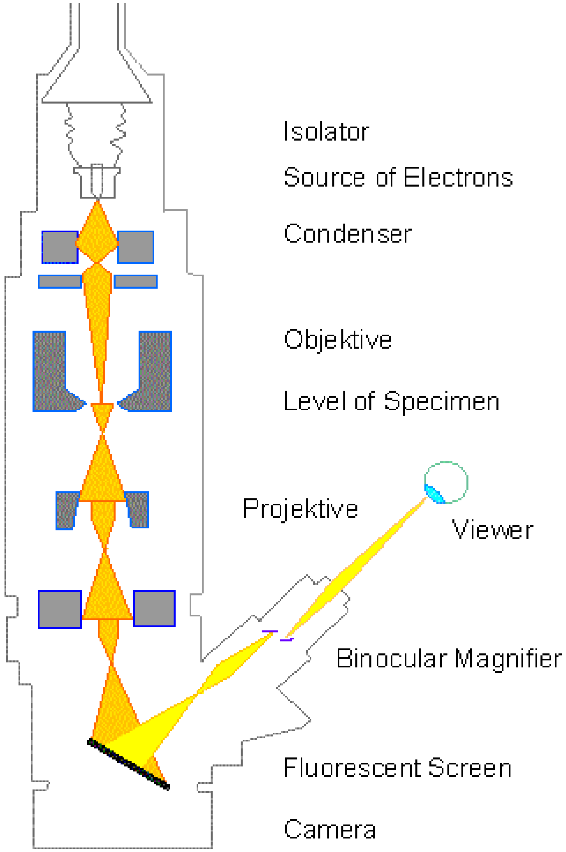


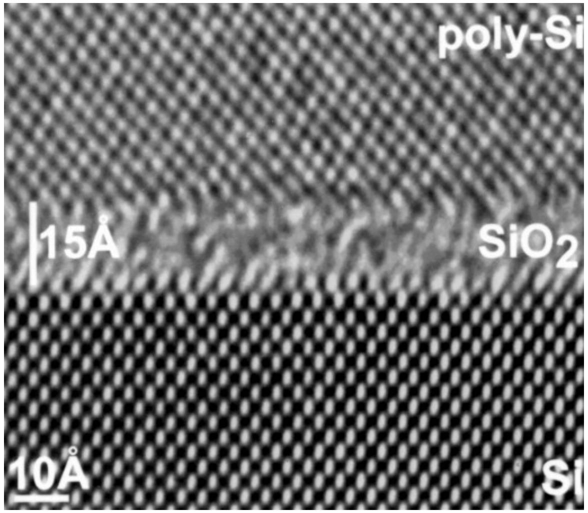


EBIC image (left) and EBIC-DLM image (right) showing non-uniform electrically active defects in a SiC epitaxial sample. Diffusion length varies by more than a factor of 4 in this sample. Non-uniformity is due to poor polishing of the SiC substrate and subsequent variation in the epitaxial film surface recombination velocity at the film-substrate interface.

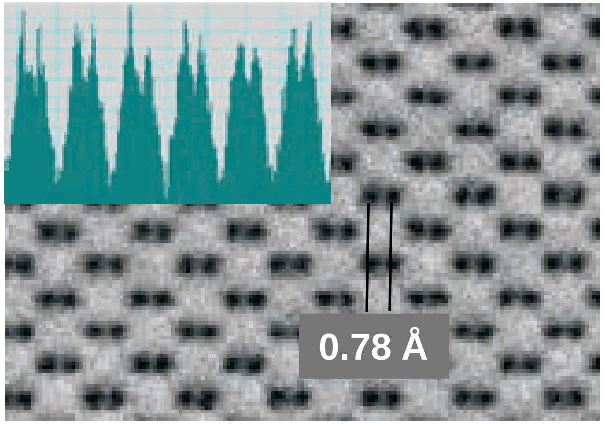
Transmission Electron Microscopy

- Electrons accelerated to ~100 – 300 keV
- Sample must be very thin so electron do not spread out





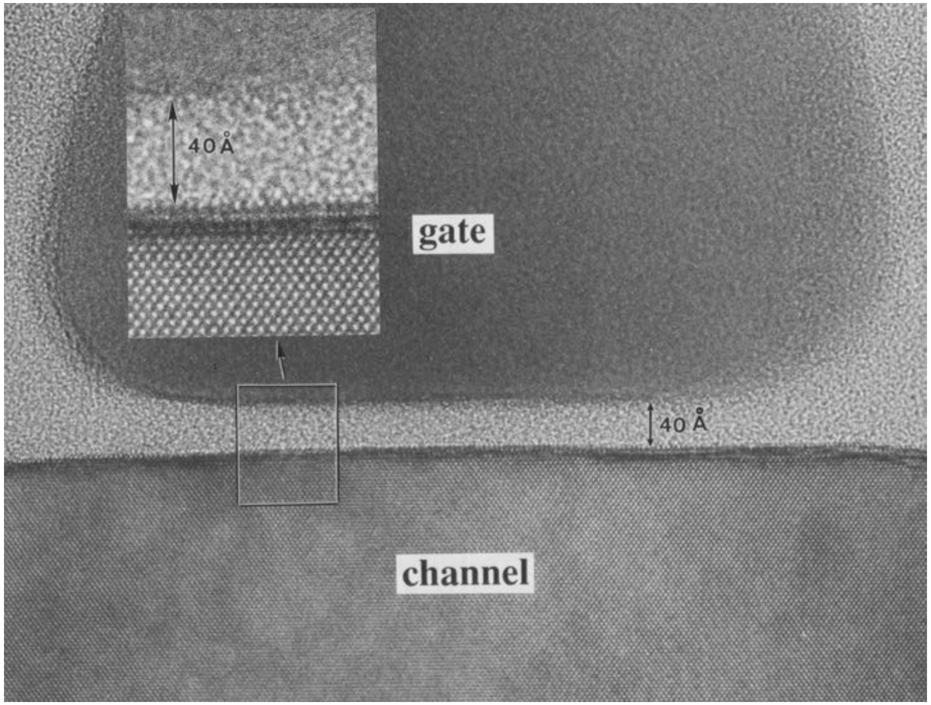
Courtesy of M.A. Gribelyuk, IBM



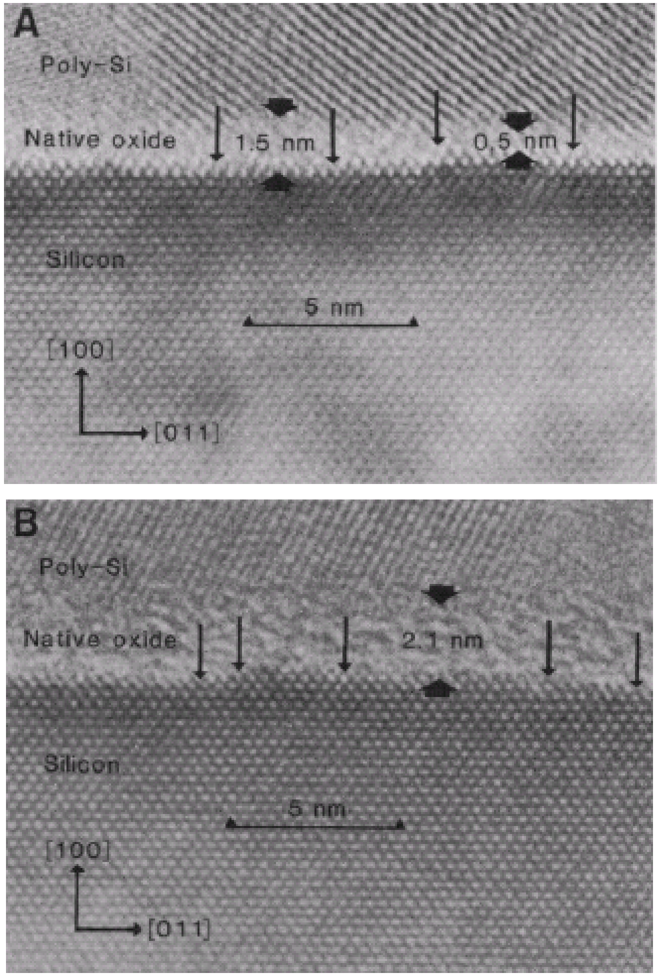
Si atoms spaced 0.78 Å

Transmission Electron Microscopy

- High-resolution TEM images of native oxide on Si
  - A: HF clean
  - B: H_2SO_4/H_2O_2 clean
  - Arrows indicate interfacial steps

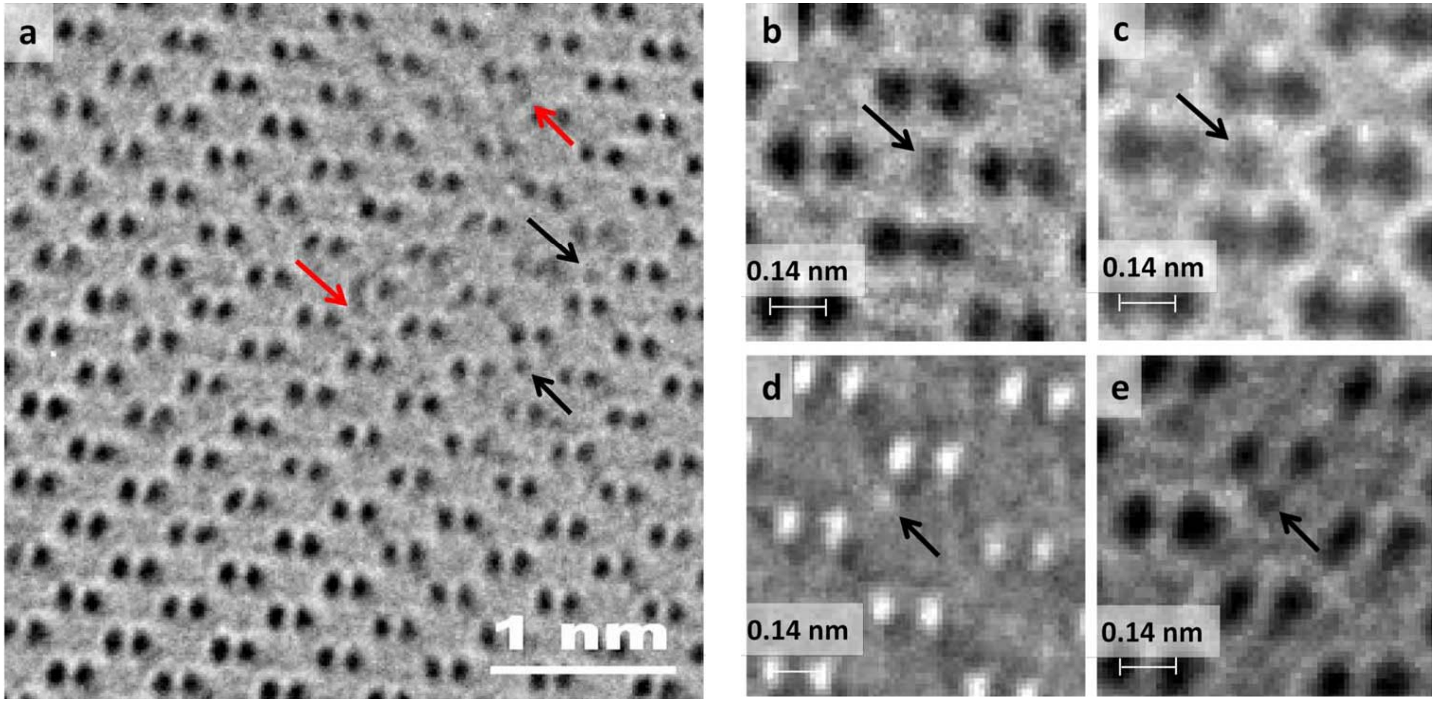


Courtesy of Y.O. Kim, Bell Labs.



A.C. Carim et al., *Science*, **237**, 630 (1987)

Ge Interstitials



Aberration-corrected images of a thin Ge crystal; black arrows: occupied interstitial sites, red arrows: dark gray show column vibrations occurring during the acquisition time

Magnified areas where an interstitial atom is observed, b and c In *T sites, d In an H site*, e in an off-center site

D. Alloyeau et al., *Phys. Rev*. **B80**, 014114, 2009.

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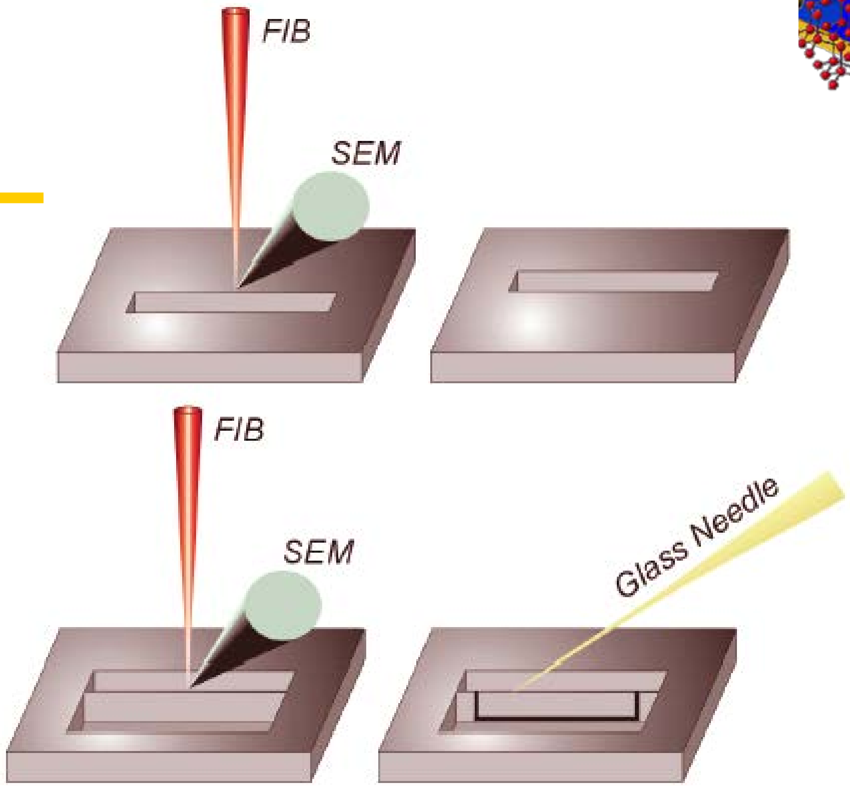
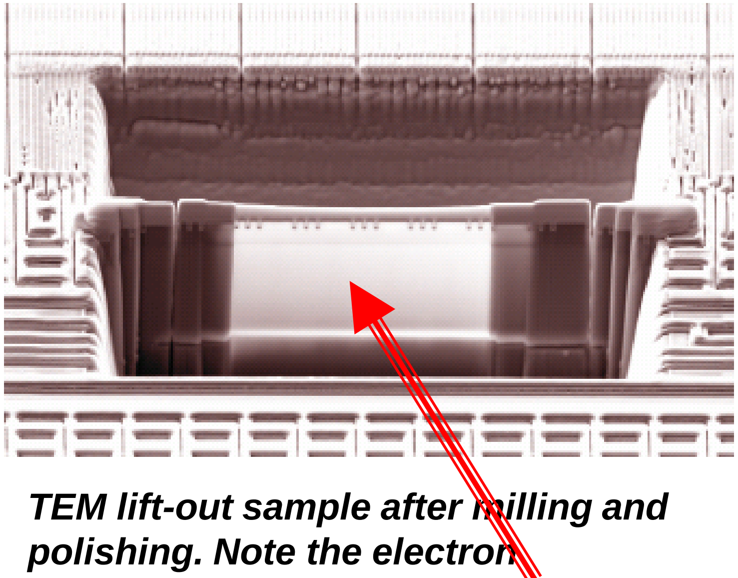
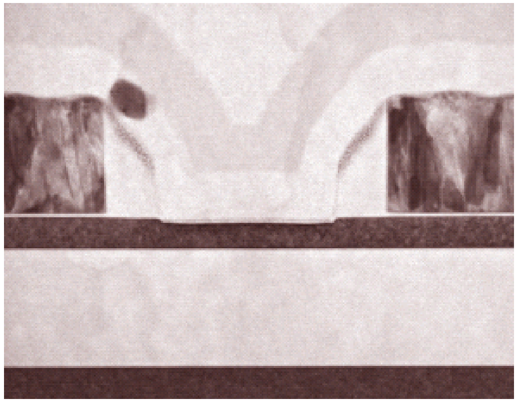
Sample Preparation
Focused Ion Beam

- Focused ion beam (FIB)
  - Ga beam
  - Focused to 5-10 nm
  - Cut holes in a sample
  - Prepare TEM samples
  - Connect metal lines



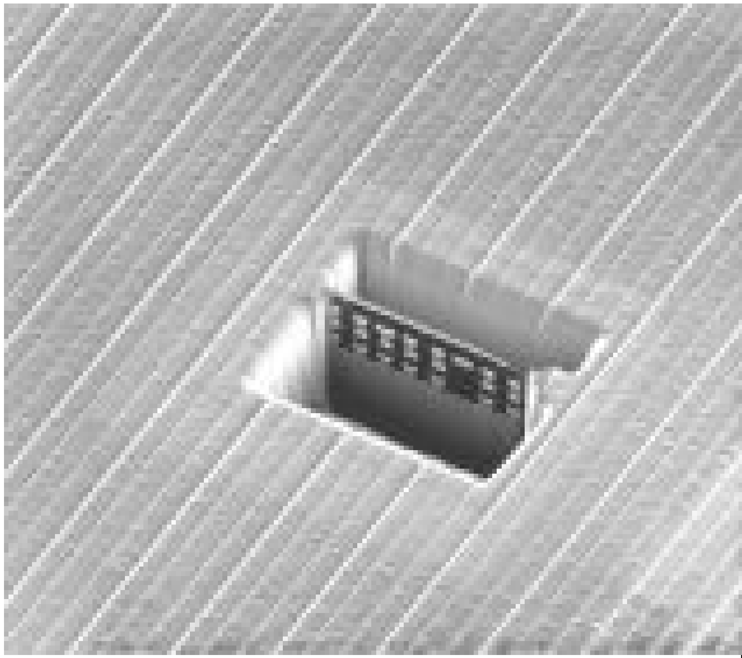


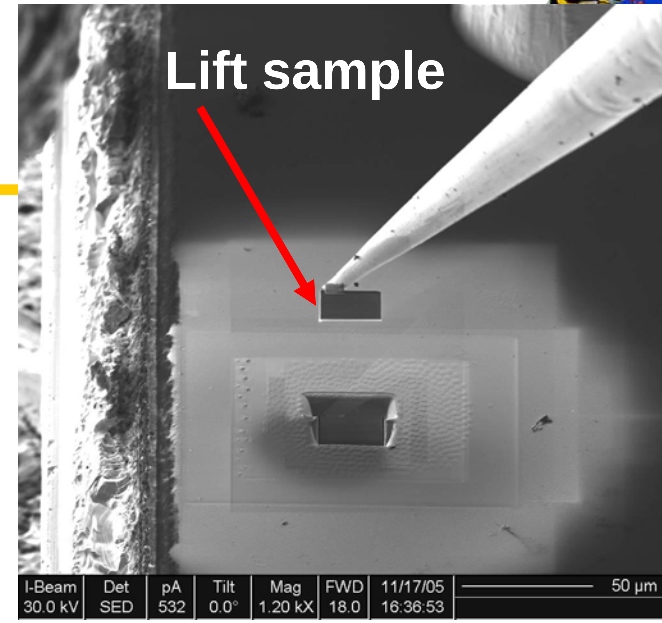
TEM lift-out sample after milling and polishing. Note the electron transparency of the thin area.

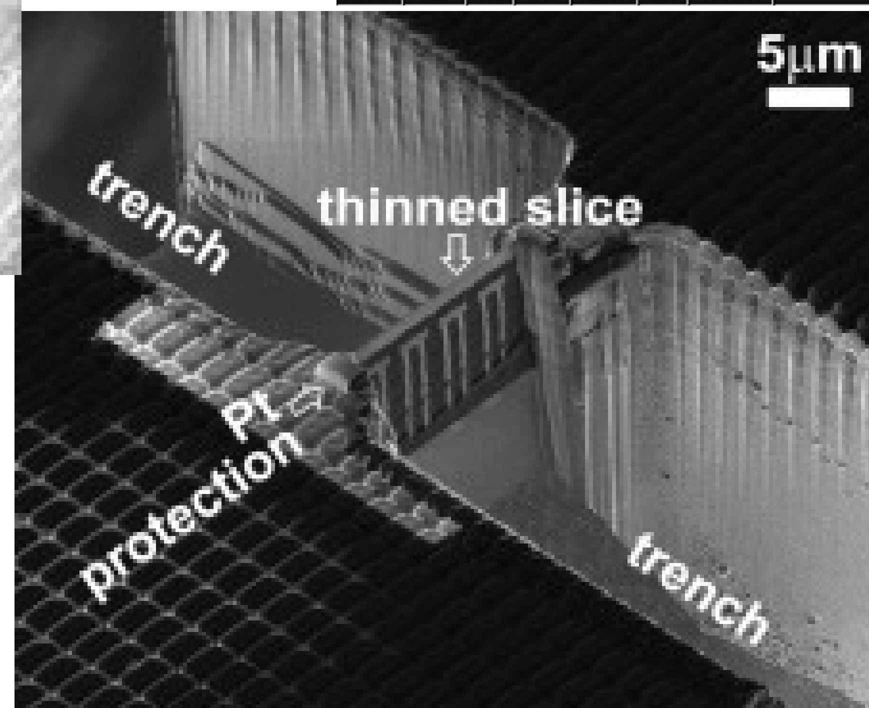


30-kV bright field STEM image of a semiconductor structure showing a small defect in the center.

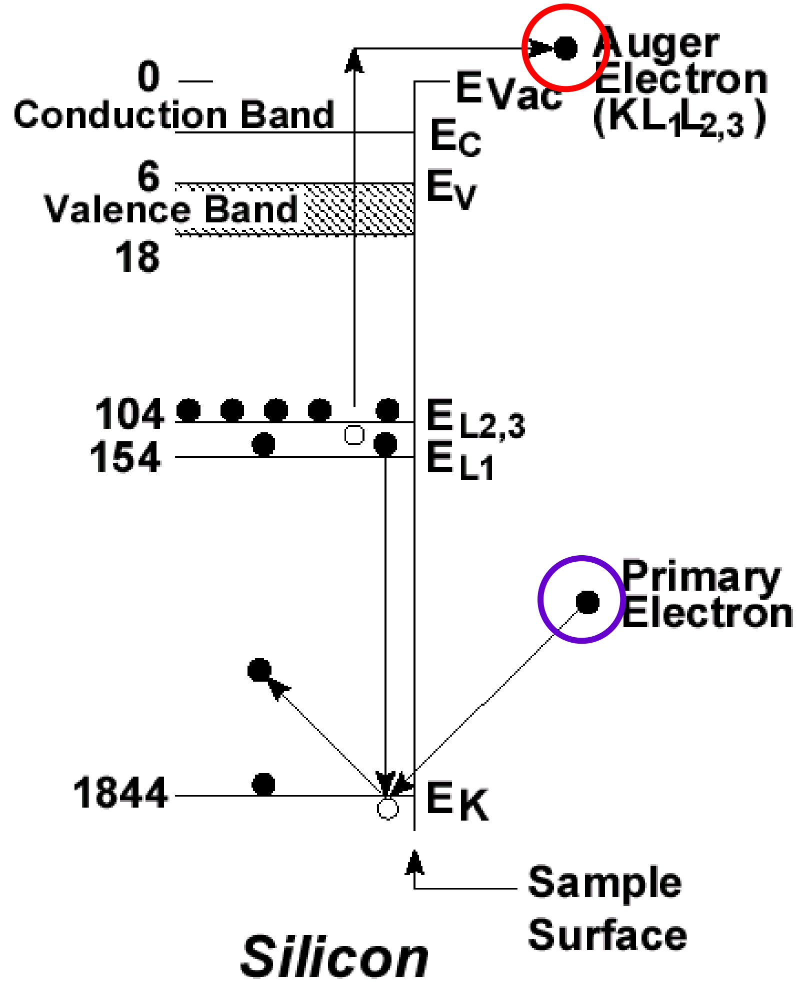
Focused Ion Beam (FIB)



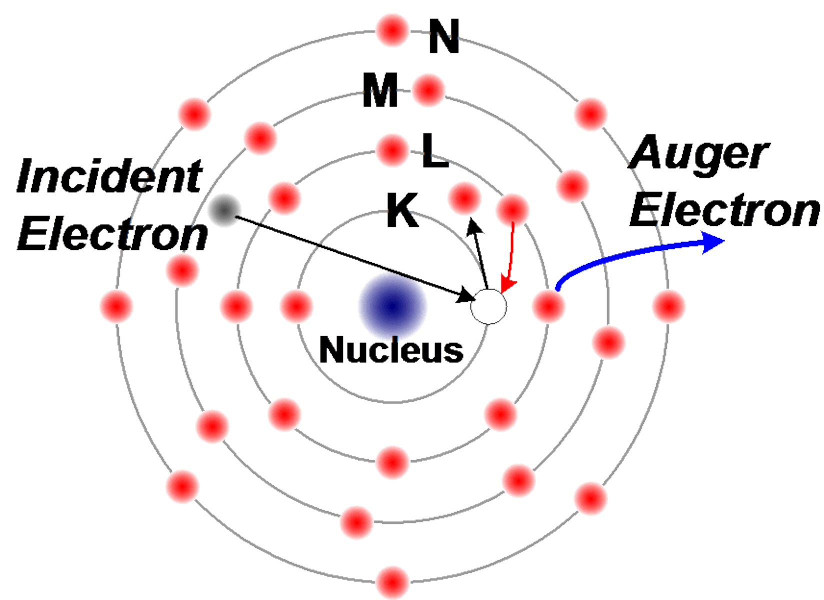




Auger Electron Spectroscopy (AES)

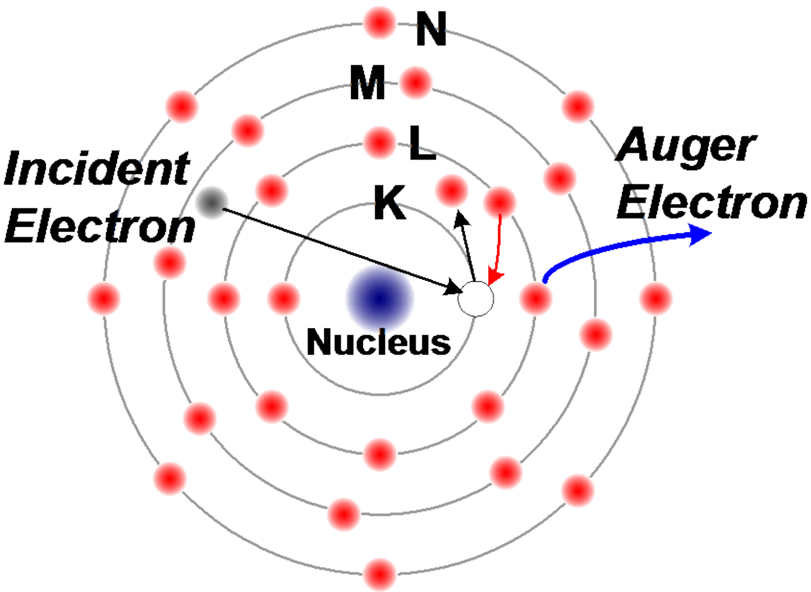


- Incident electron knocks electron out of K shell
- L shell electron falls into vacancy (hole)
- A second L shell electron is ejected



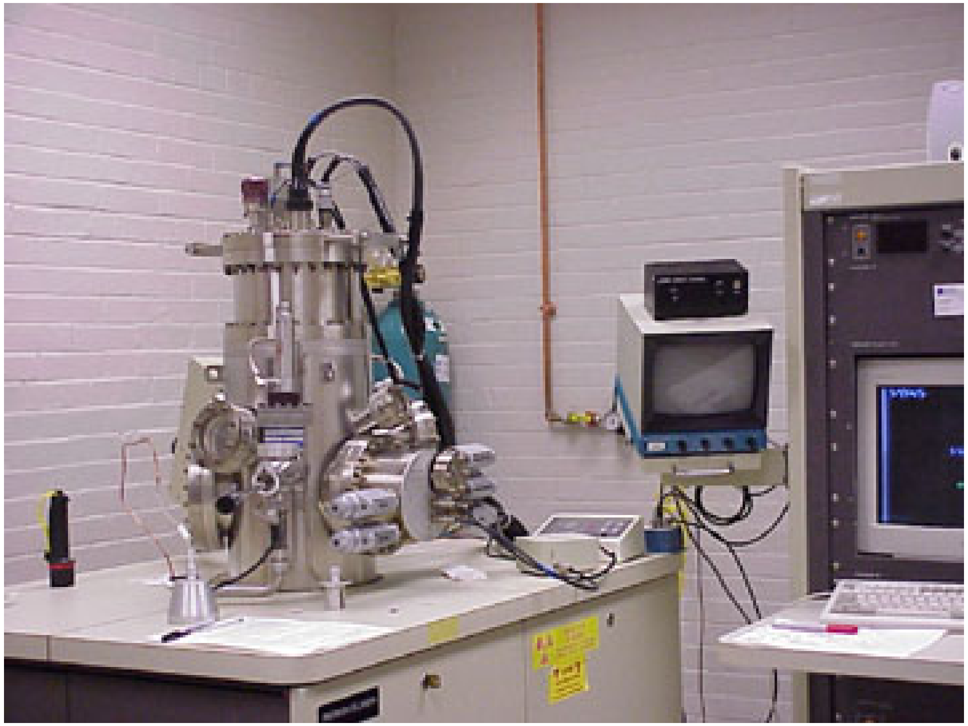
Auger Electron Spectroscopy

- *Advantages:* Nondestructive technique; determines major components of the sample in a single analysis. Can analyze all elements except H and He
- *Limitations:* Samples first 10 - 20 Å; not very sensitive; sample can charge up
- *Sensitivity*: 10^{19} - 10^{20} cm^{-3}
- *Volume sampled*: ~ 1mmx1mmx10Å = 10^{-9} cm^3
- *Applications*: Surface analysis. Combining AES with sputtering gives depth information. Resolution is improved with scanning AES (~ 1000 Å or less)



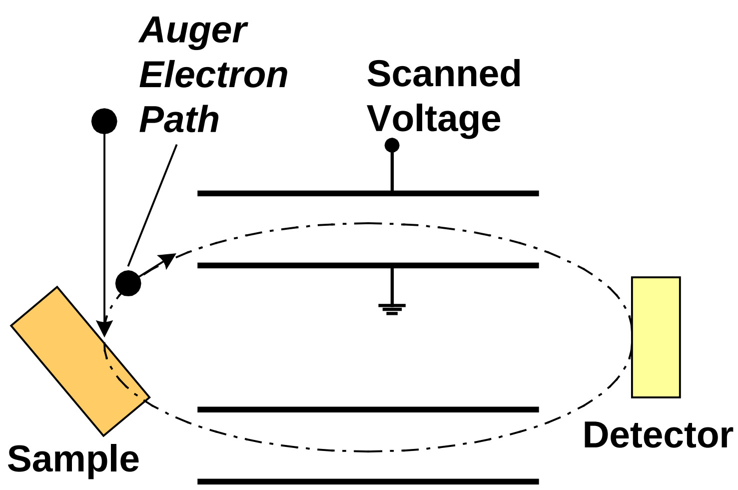
Auger Electron System

- AES requires *high vacuum* since it is a surface sensitive technique



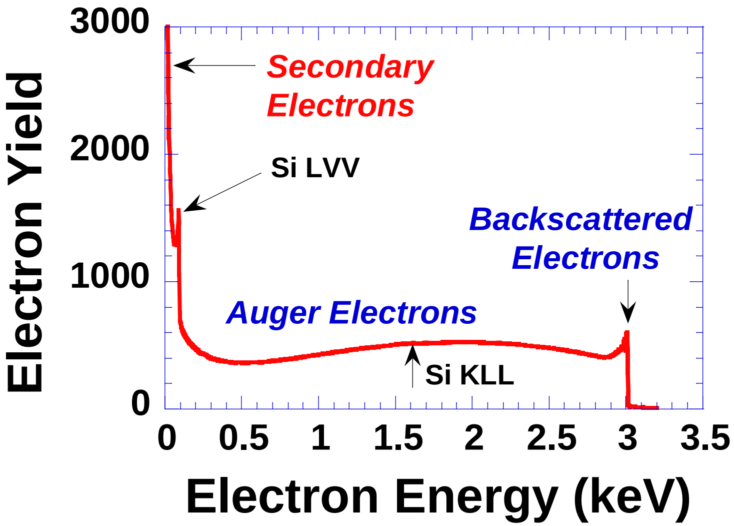
AES Detector

- The cylindrical mirror analyzer is a common electron energy detector
- The voltage on the outer electrode is scanned
- For each voltage a certain energy electron is transmitted



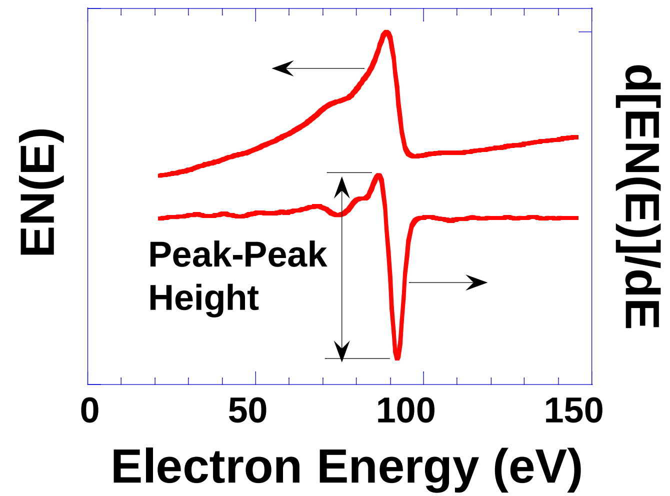
AES Signal Analysis

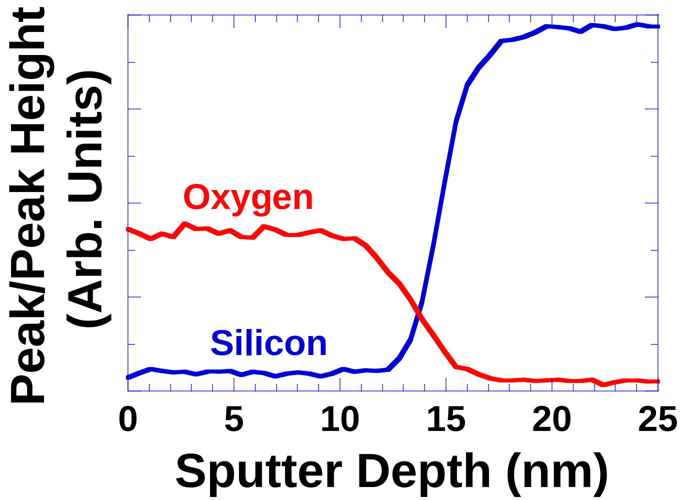
- **It is frequently difficult to extract AES signals from small "bumps" on the *Electron Yield – Electron Energy* curve**
- **AES signals are easier to analyze if the curve is differentiated**

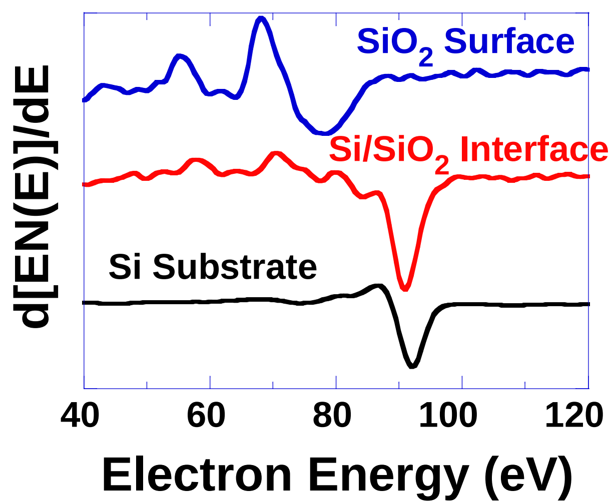


Auger Electron Spectroscopy

- Element identification
- Molecular information
- Depth profile

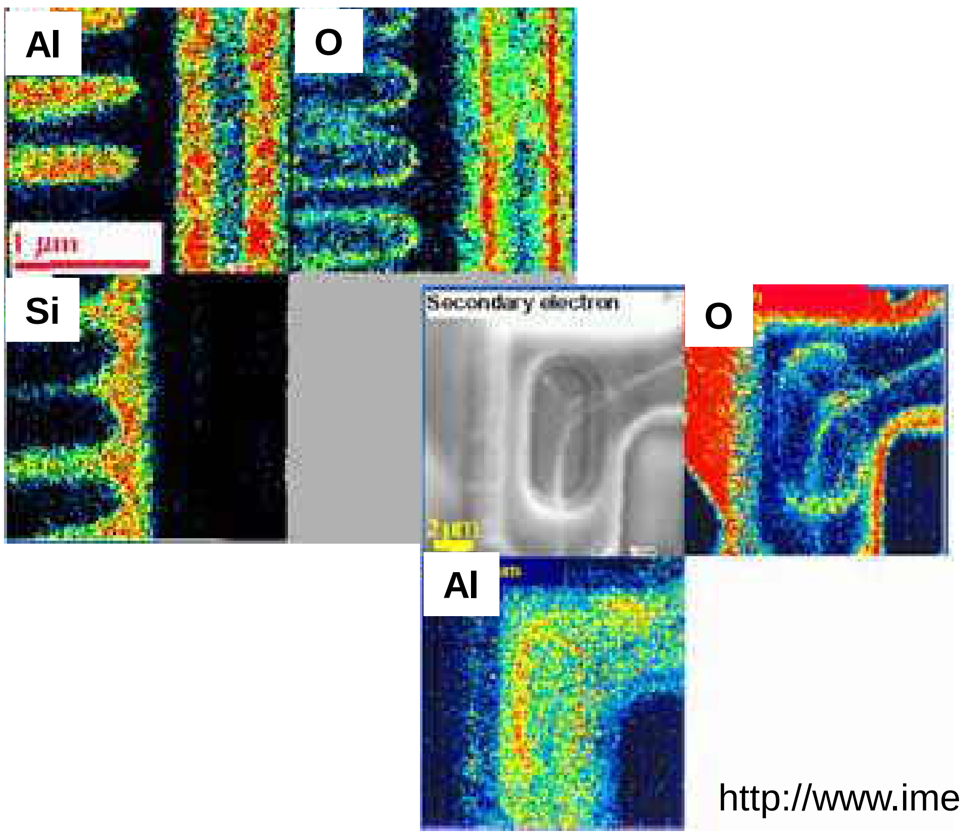


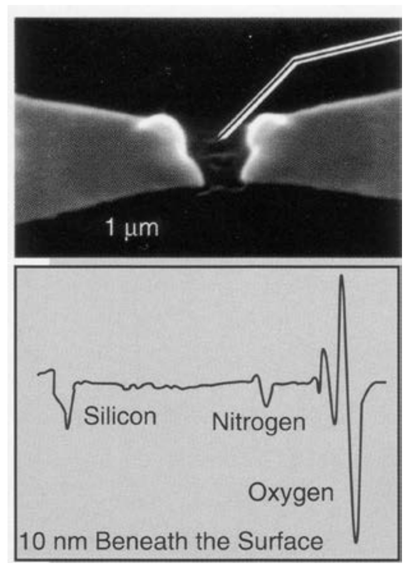




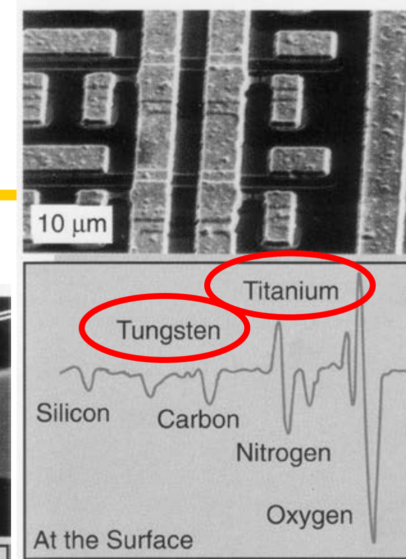
Auger Electron Spectroscopy

- AES can give
  - Spectrum
  - Profile
  - Maps





10 nm below surface, no TiW.



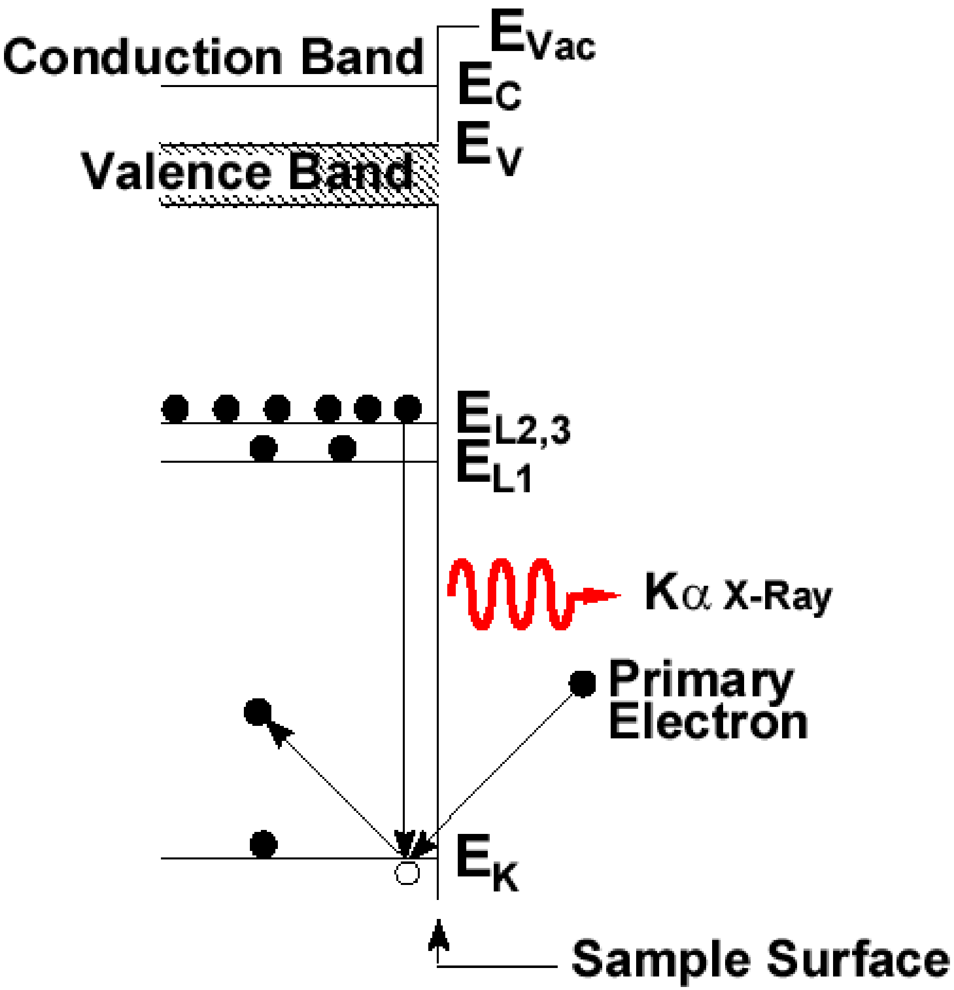
Residual TiW monolayer in PROM link was identified with scanning AES; responsible for charge leakage.

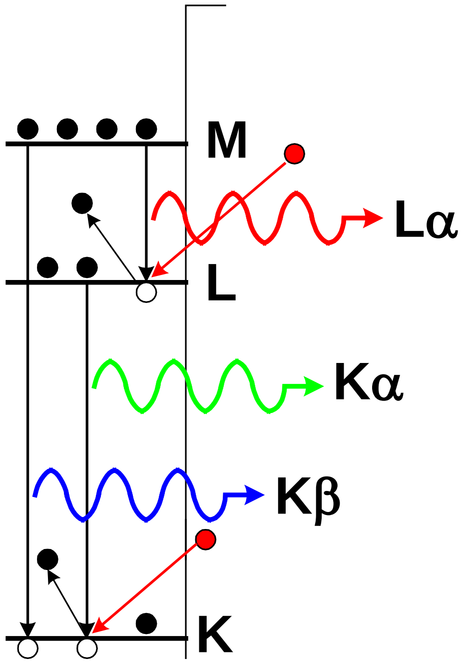
Courtesy of T.J. Shaffner, Texas Instruments

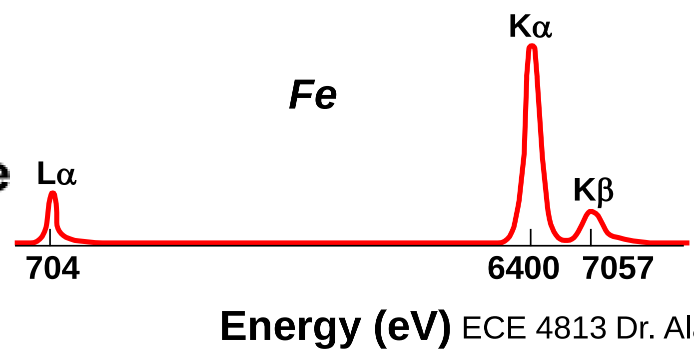
http://www.ime.org.sg/far/far_aes.htm

Electron Microprobe (EMP)

- Incident electron knocks electron out of K shell
- L shell electron falls into vacancy (hole)
- Energy is emitted as an X-ray

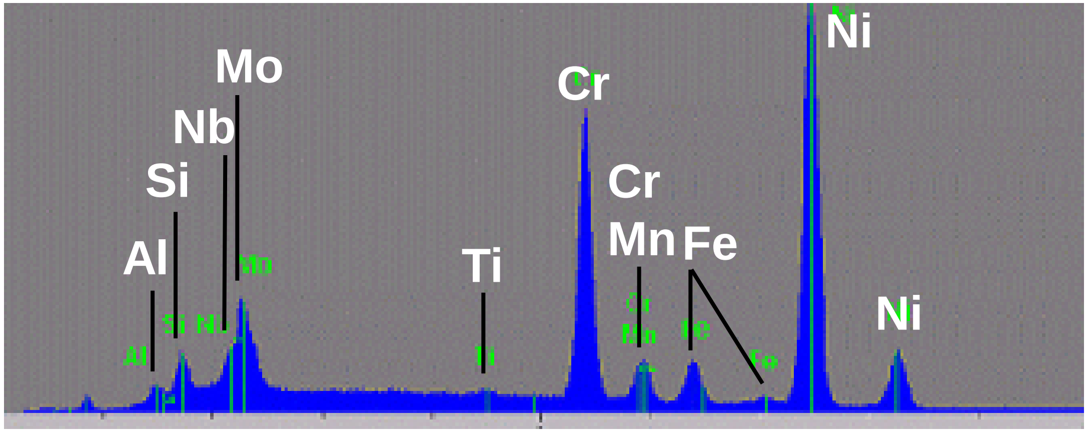






Electron Microprobe

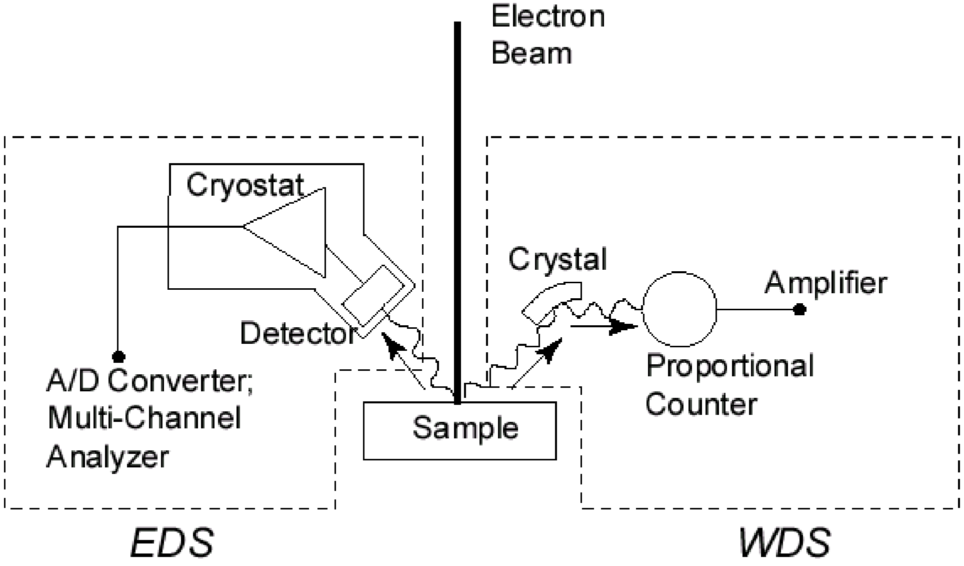
- *Advantages:* Nondestructive technique; trace impurities and major components in a single analysis. Two-dimensional information by scanned beam.
- *Limitations:* Poor sensitivity for elements with Z < 10. X-ray resolution determined by the electron absorption volume not the e-beam size.
- *Sensitivity*: 10^{18} - 10^{19} cm^{-3}
- *Volume sampled*:~ 10 μmx10 μmx10 μm = 10^{-9} cm^3
- *Applications*: Rapid analysis of thin films and bulk samples. Two-dimensional elemental display.



Nickel-based alloy consisting of *nickel*, *chromium*, *manganese*, *titanium*, *silicon*, *molybdenum*, and *aluminum*

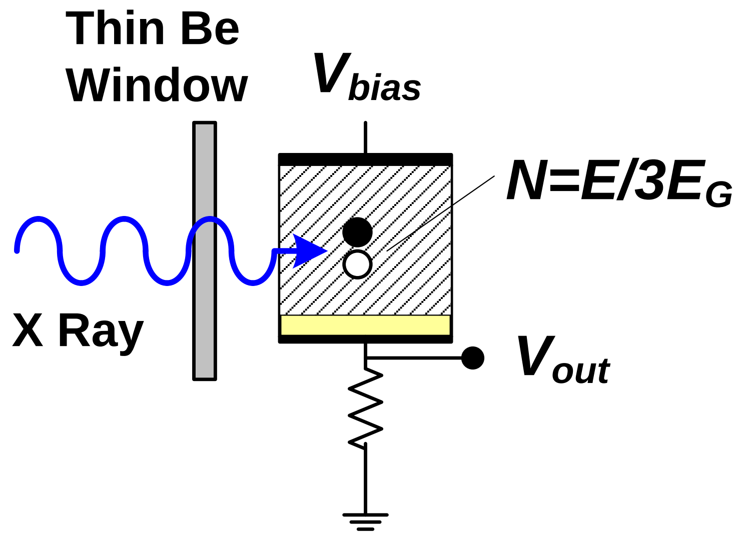
Electron Microprobe

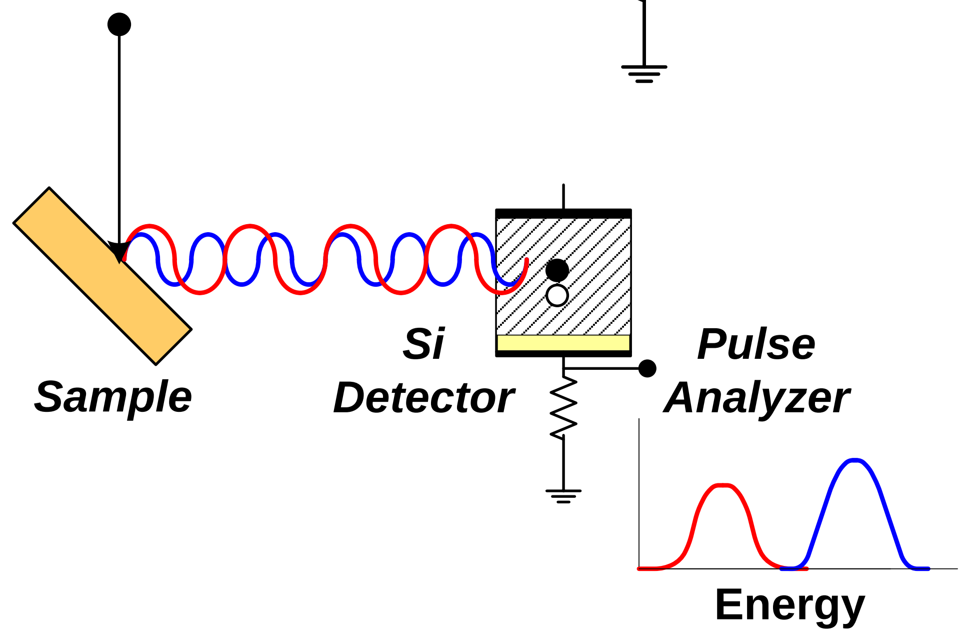
- The X-rays can be detected by
  - Energy-dispersive spectrometer (EDS)
  - Wavelength-dispersive spectrometer (WDS)



Energy-Dispersive Spectrometer

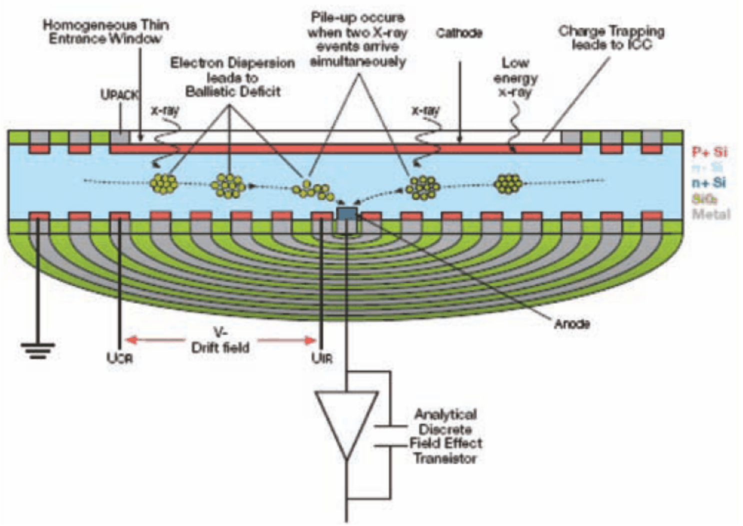
- Routinely used; simpler than WDS
- Uses semiconductor diode detector
- Electron beam with energy *E* creates *N* electron-hole pairs
- *Si:* E = 30 keV, E_G = 1.1 eV
  $\Rightarrow N \approx$ 9000 ehp

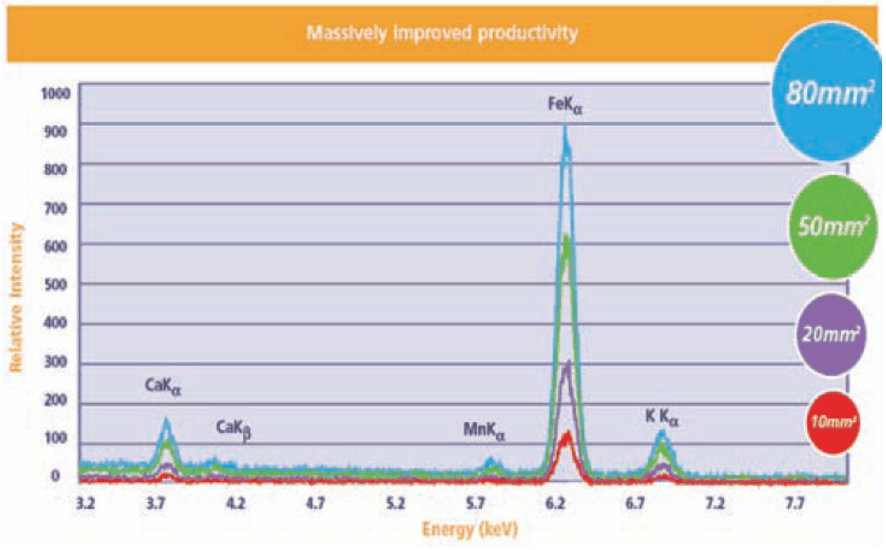




Large Area Si Drift Detector

- **The detector anode is small, collection area is large**
  - **Lower capacitance and lower voltage noise than conventional detector**
  - **Low time constant minimizes the effect of leakage current**
  - **Higher temperature cooling instead of liquid nitrogen**

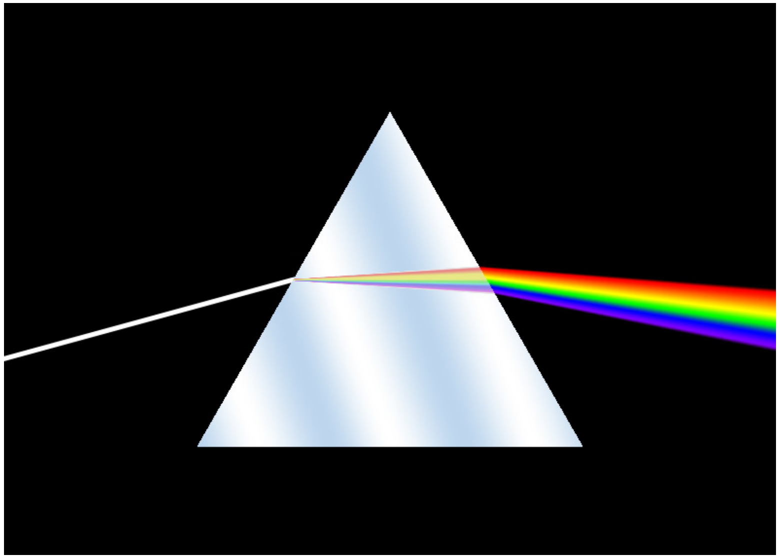




C. Collins, New Large Area Silicon Drift Detectors - Fast Analysis without Compromise, *Microscopy Today*, **17**, 6, Jan. 2009.

Prisms and Gratings

- **Why does white light appear colored after passing through a prism or a grating?**

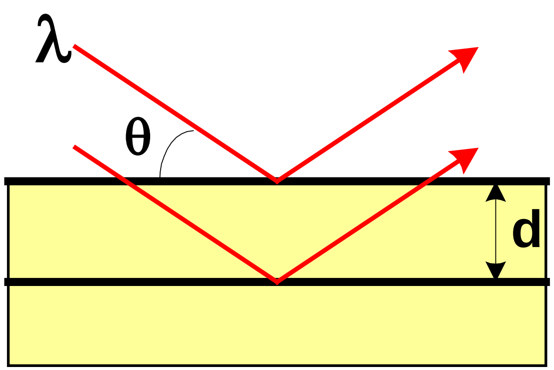


Prism

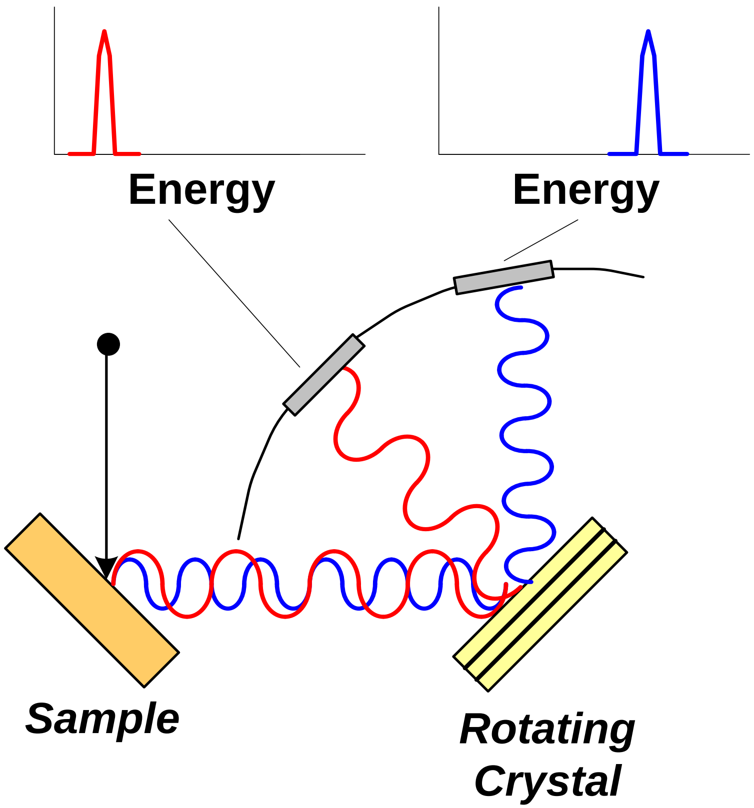
Grating

Wavelength-Dispersive Spectrometer

- X-rays undergoing constructive interference are reflected
- Changing the crystal angle selects different wavelengths

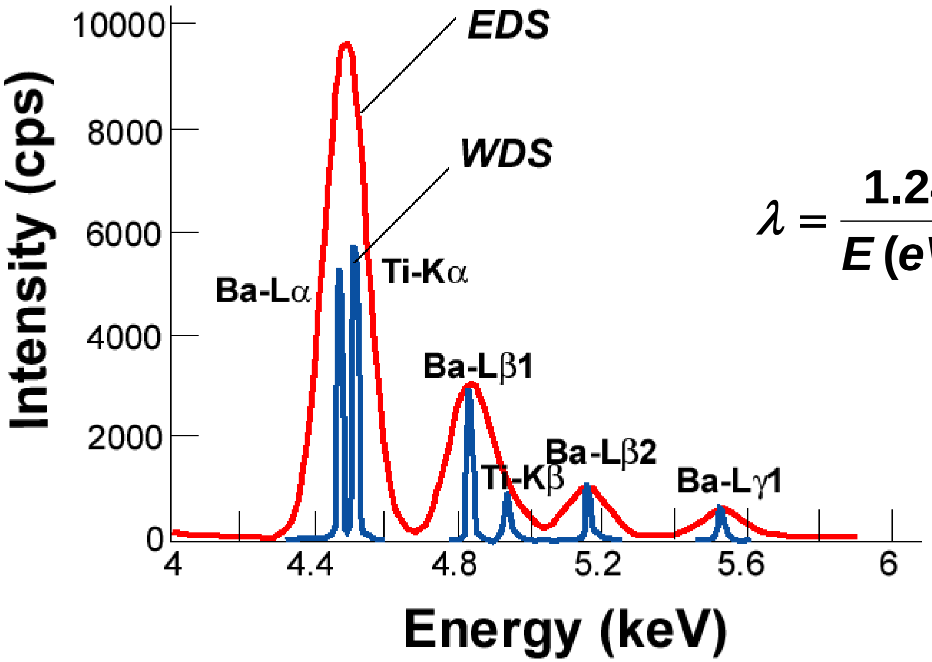


$$n\lambda = 2d\sin\theta$$



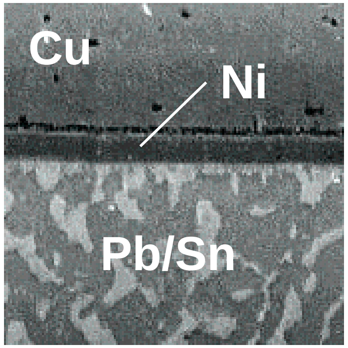
EDS Versus WDS

- WDS has higher resolution but is more difficult to implement
- It takes several crystals for different wavelengths



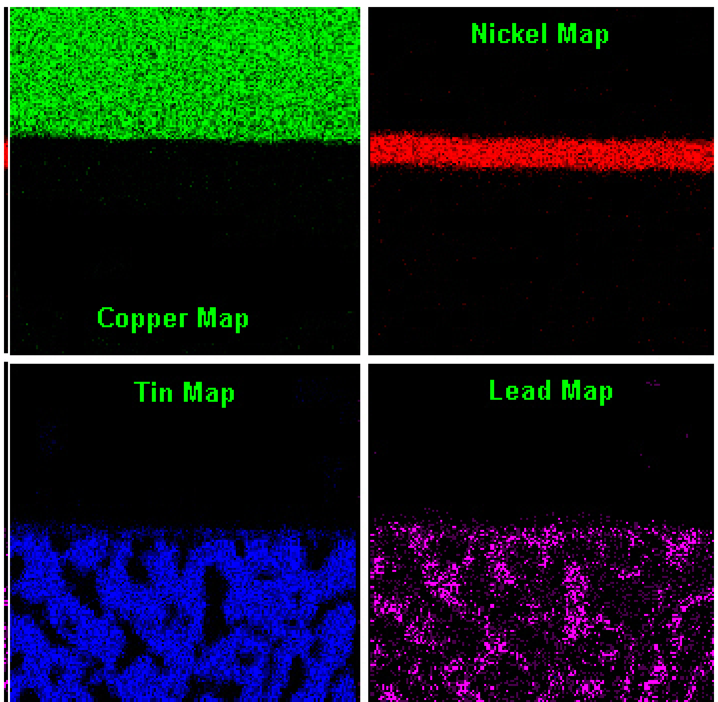
$$\lambda = \frac{1.24}{E\,(eV)}\ (\mu m)$$

Electron Microprobe



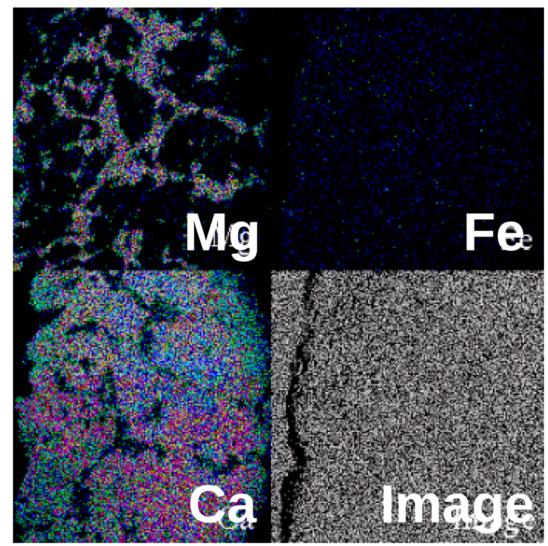
SEM cross-sectional image of *Pb/Sn* solder joint on *Ni*-plated *Cu* wire

500x Magnification



Kidney stone

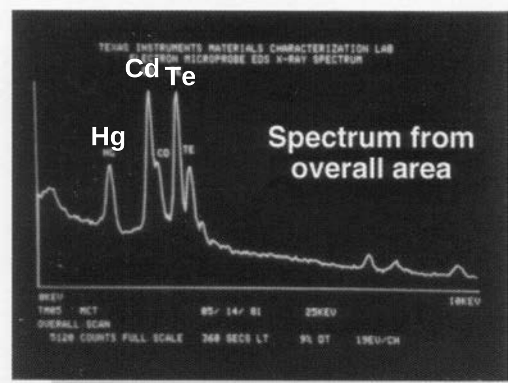
150x Magnification



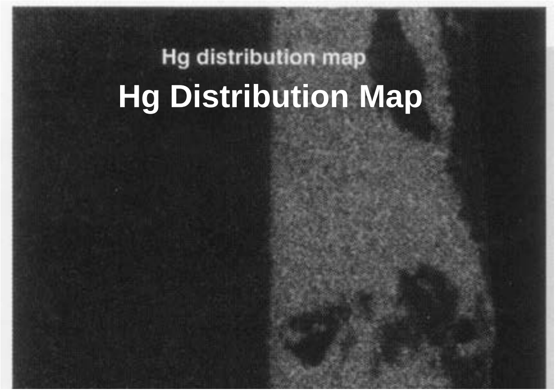
www.seallabs.com/edx.html

Electron Microprobe

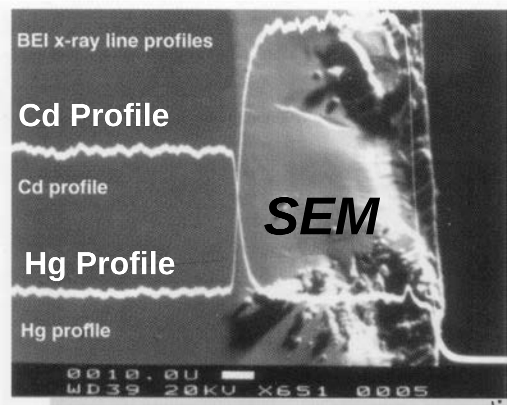
Spectrum

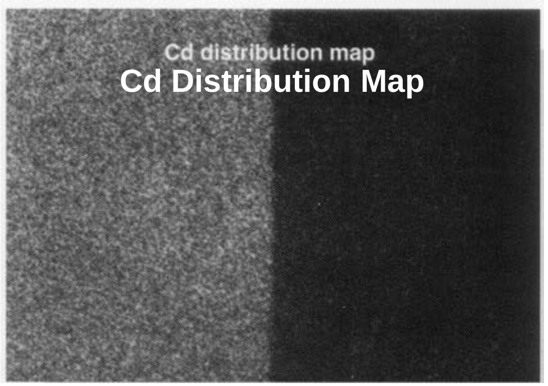


Distribution Maps



Line Scan





Courtesy of T.J. Shaffner,
Texas Instruments

Review Questions

- What determines the magnification in an SEM?
- What is detected in *Auger electron spectroscopy*?
- What is detected in *electron microprobe*?
- What is the detection mechanism in energy dispersive spectroscopy (*EDS*)?
- What is the detection mechanism in wavelength dispersive spectroscopy (*WDS*)?
- How are X rays generated?
- *AES* or *EMP*: which has higher resolution? Why?